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Thermodynamic analyses of municipal solid waste gasification plant integrated with solid oxide fuel cell and Stirling hybrid system

Masoud Rokni

Technical University of Denmark, Department of Mechanical Engineering, Thermal Energy Section, Building 403, 2800 Kgs Lyngby, Denmark

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ABSTRACT

Municipal solid waste (MSW) can be considered a valid biomass to be used in a power plant. The major advantage is the reduction of pollutants and greenhouse gases emissions not only within large cities but also globally. Another advantage is that by their use it is possible to reduce the waste storage in landfills and devote these spaces to other human activities. It is also important to point out that this kind of renewable energy suffers significantly less availability which characterizes other type of renewable energy sources such as in wind and solar energy.

In a gasification process, waste is subject to chemical treatments through air or/and steam utilization; the result is a synthesis gas, called “Syngas” which is principally composed of hydrogen and carbon monoxide. Traces of hydrogen sulfide could also be present which can easily be separated in a desulfurization reactor. The gasification process is usually based on an atmospheric-pressure circulating fluidized bed gasifier coupled to a tar-cracking vessel. Syngas can be used as fuel in different kind of power plant such as gas turbine cycle, steam cycle, combined cycle, internal and external combustion engine and Solid Oxide Fuel Cell (SOFC).

In the present study, a MSW gasification plant integrated with SOFC is combined with a Stirling engine to recover the energy of the off-gases from the topping SOFC cycle. Detailed plant design is proposed and thermodynamic analysis is performed. Relevant parameters have been studied to optimize the plant efficiency in terms of operating conditions. Compared with modern waste incinerators with heat recovery, the gasification process integrated with SOFC and Stirling engine permits an increase in electricity output up of 50%, which means that the solid waste gasification process can compete with incineration technologies. Moreover waste incinerators require the installation of sophisticated exhaust gas cleaning equipment that can be large and expensive and are not necessary in the studied plant.

E-mail address: MR@mek.dtu.dk.
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Introduction

Owing to the ever-increasing demand for more efficient power production and distribution, improving production and distribution efficiencies and reducing pollutant emissions continue to be the main areas of research and development in the field of electricity production. Currently, there is an increased interest in developing distributed systems consisting of small-scale facilities at a single location, allowing electricity and heat to be produced and distributed close to the end user, thereby minimizing the costs associated with transportation [1,2].

The term "biomass" refers to vegetable and animal substances that do not have a fossil origin and can be used as fuel in a power plant for the production of electrical energy. Biomass derived from living or recently living biological organisms can be considered to be a particular kind of renewable energy source, because the carbon dioxide released into the atmosphere by their use is compensated for by the amount of carbon absorbed during their life. In the case of such biomass, the most important pollutants linked to biomass utilization are related to transport, manufacture, and transformation processes. Municipal solid waste (MSW) is one such type of biomass and is suitable for use in power plants. It presents some advantages such as the reduction of pollutants and greenhouse gas emissions and the possibility of reducing storage in landfills, as a result of which these spaces can be devoted to other human activities.

It is also important to point out that this kind of renewable energy has a significantly low availability, which also characterizes the other types of renewable energy sources such as wind and solar energy. As suggested by Morris and Waldheim [3], a well-designed waste management system should prevent waste generation, recycle waste materials, reduce landfill disposal to a minimum, incinerate with energy recovery at efficiencies comparable to alternative technologies, must utilize sophisticated exhaust gas cleaning equipment, and must incorporate gasification processes.

In a gasification process, the waste is subjected to chemical treatments through air or steam utilization. Synthesis gas, also known as "syngas", which is principally composed of H_2 and CO, is produced as a result of the gasification process. Traces of H_2S and other contaminants may also be present and can be separated in a desulfurization reactor and/or a fuel conditioning system. The gasification process is usually performed in a fluidized bed gasifier under atmospheric-pressure, coupled with a tar-cracking vessel. The produced gas is then cleaned and the syngas can be used as a fuel in various kinds of power plants such as gas turbine cycles, steam cycles, combined cycles, internal and external combustion engines, and SOFCs.

SOFCs are one of the most promising type of fuel cells, particularly in terms of energy production. They are expected to produce clean electrical energy at high conversion rates with low noise and low pollutant emissions [4]. SOFC stacks may soon enter the commercialization phase. In addition, small Stirling engines are also approaching the commercialization phase. Therefore, it would be interesting to integrate these two technologies into a single system that would combine the benefits of each system, thereby establishing a new technology. By integrating this combined system with a gasification plant that gasifies MSWs, electricity and heat energy could then be produced in an environmentally friendly manner.

To date, studies on the use of syngas generated from coal and biomass gasification as a feed for SOFCs have been carried out [5,6]. The use of synthetic wood gas for operating SOFCs has also been experimentally studied [7] and it has been shown that wood gas obtained from air gasification always provides a stable performance, whereas the performance results for the wood gas obtained from steam gasification are inconclusive.

The exhaust temperatures of SOFCs are high owing to the high operating temperature of the cells. Additionally, since the fuel utilization in the fuel cell is less than 100 percent, the unreacted fuel needs to be combusted in a burner. The combustion process, in turn produces even hotter off-gases that are perfectly suited for use in heat engines such as a Stirling engine, for the production of power and heat for domestic purposes.

Numerous studies in the literature have investigated SOFC-based power systems and have reported high thermal efficiencies. However, the majority of these studies use gas turbines as the bottoming cycle [8–10]. In addition, steam turbines have also been used as bottoming cycles [11,12], resulting in high plant efficiencies without pressurizing the fuel cells. Only a few studies have been carried out with a Stirling engine as the bottoming cycle and a fuel cell cycle as the topping cycle [1,2]. At present, using the Brayton and Rankine cycles as bottoming cycles appears to be the most practical method, owing to the maturity of these technologies. The development trends in the field of SOFCs suggest that the operating temperature of the SOFCs will decrease in the future. As a result, using a gas turbine as the bottoming cycle will become less beneficial over time.

Introducing a heat engine (such as a Stirling engine) as the bottoming cycle for SOFCs instead of gas turbines and steam cycles has several advantages. Such a hybrid cycle is significantly less complex and heat production can match the high electrical powers obtained (high heat-power ratio). In addition, small-scale combined heat and power (CHP) plants suitable for hotels, hospitals, and shopping centers can be built at much lower plant costs.

Integrated gasification SOFC systems have also been previously studied [13–15]. Coal gasification with a complex syngas fuel conditioning system has also been integrated with SOFCs and studied widely in the literature [16,17]. However, there has been a void in research in the area of integrated MSW gasification-SOFC-Stirling CHP plants in the literature, which form the basis for this study.

The present work is a thermodynamic investigation of integrated systems consisting of an MSW gasification plant, SOFCs, and a Stirling engine. The syngas produced from the gasification unit is used as the fuel for the SOFC plant that also functions as a topping cycle for a Stirling engine, which uses the heat from the off-gases released from the topping cycle. The net capacity of the system is 120 kW, which is suitable for use in decentralized CPH plants. The gasifier type used in this study is adopted from the two-stage autothermal (air-blown)